

2021-05-01

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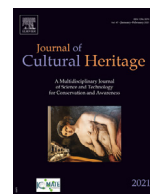
Barrientos, F

<http://hdl.handle.net/10026.1/18217>

10.1016/j.culher.2021.03.009

Journal of Cultural Heritage

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Review

Computational methods and rural cultural & natural heritage: A review



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ARTICLE INFO

Article history:

Received 13 November 2020

Revised 28 March 2021

Accepted 29 March 2021

Available online 24 April 2021

Keywords:

Cultural heritage

Natural heritage

Rural areas

Computational methods

Modelling

ABSTRACT

Cultural and Natural Heritage (CNH) are both irreplaceable sources of life and inspiration, according to the UNESCO definition. Rural areas represent outstanding examples of cultural, either tangible or intangible, and natural heritage. While rural areas are facing a socio-economic and demographic crisis all over the world, CNH need not only to be safeguarded, but also promoted as a driver for competitiveness, growth and sustainable and inclusive development. This paper goes deeper into the study of computational methods (CMs) applied to modelling CNH in rural areas by looking at how computational methods can support CNH promotion and valorisation to transform rural areas into laboratories for the demonstration of sustainable development through improving the unique potential of their heritage. To this end, different computational methods have been studied and classified according to their scope and application area parameters, showing some correlation among the said parameters and the class of computational method. Apart from how CMs have been applied, whether it is possible to scale up these CMs elsewhere has also been considered.

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1. Introduction

Europe's rural areas host outstanding examples of Cultural and Natural Heritage that need, not only to be safeguarded, but also promoted as an engine for competitiveness, growth and sustainable and inclusive development [1]. According to the PAHIS 2020 Plan [2], there has been a deepening of the so-called Cultural Heritage Economy in recent years, in accordance with current criteria which establish that cultural heritage assets should no longer be perceived as a burden but as a resource capable of generating development and social cohesion.

This review aims to go deeper into the study of rural regeneration paradigms based on heritage, capable of converting rural areas into laboratories for the demonstration of sustainable development by improving the unique potential of their heritage. To this end, different models, or success stories, have been studied. Most of them are complex systems in which intuitive analytical solutions

are not available, and computational models can be used to make predictions of the system's behaviour under different conditions. As defined by [3], computational methods are mathematical models used to numerically study the behaviour of complex systems by means of a computer simulation.

Depending on the scope, models can be predictive or descriptive. The former focus mainly on precision and its key aspects are simplicity and interpretability [4], while the latter focus more on pattern recognition among datasets, providing knowledge on a specific problem [5].

According to the UNESCO definition [6] 'the culture cycle captures all of the different phases of the creation, production, and dissemination of culture'. The term *culture cycle* suggests interconnections across these activities, including the feedback processes by which activities (consumption) inspire the creation of new cultural products and artefacts. Most of the activities related to CNH occur in the phases 'Dissemination', 'Exhibition and Transmission' and 'Consumption/Participation', highlighted in Fig. 1.

Particularly relevant for rural heritage is the ICOMOS-IFLA Principles concerning rural landscapes as heritage [7]. This defines the principles of actions to ensure the understanding, protection, sus-

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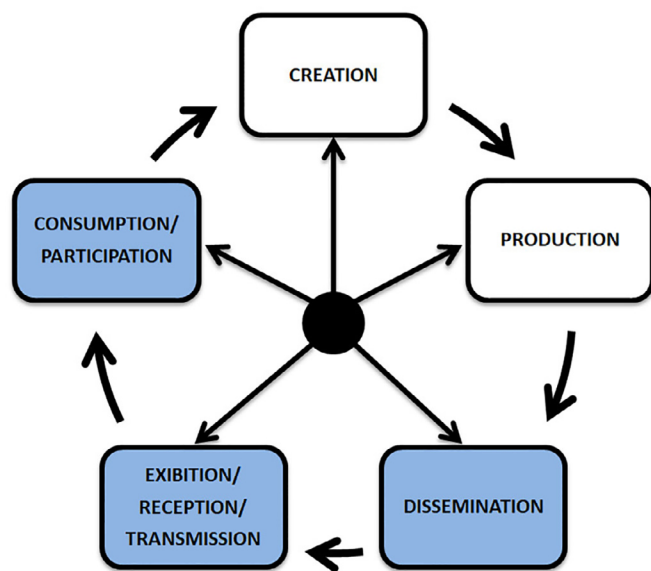


Fig. 1. The Cultural Cycle, according to the UNESCO Framework for Cultural Statistics, highlighting those phases related to CNH (adapted from [6]).

tainable management, and transmission of rural landscapes as heritage.

To the best of our knowledge, there is no similarly comprehensive study reviewing the literature that involves computational methods applied to modelling cultural and natural heritage in rural areas.

This paper is organised as follows: Section 3 describes the methodology used for the literature review. Section 4 explains the results obtained and how the bibliographic references have been analysed and grouped; while Section 5 discusses the results. Finally, the main conclusions and further research are outlined in Section 6.

2. Research aims

Rural areas are facing challenges such as ageing and depopulation. Heritage based regeneration plans can contribute to the sustainable development of these rural areas. This is a complex task, however, where a trade-off among the different regeneration plans and the limited available resources should be found and where computational methods can be useful to predict the best strategy.

This paper summarises the literature found on computational methods (CMs) applied to Cultural and Natural Heritage (CNH). The authors have a special interest in rural heritage, so the first classification criterion has been the scope, differentiating between rural and urban use-cases; while the second criterion has been the area of application, in terms of cultural or natural heritage.

In particular, a structured literature review has been conducted to collect relevant references by combining Narrative Literature Review (NLR) and Systematic Literature Review (SLR).

The result of the analysis is the available body of knowledge and trends in computational methods applied to heritage modelling. It is worth noting that not every computational method is suitable for every case, depending on characteristics, application area and scope.

3. Methodology

The capacity of rural areas to reap the opportunities offered by new technologies and digitisation should be improved, boosting resilience to related risks. Cultural and natural heritage is a local as-

set that can contribute to the sustainable development of these rural areas. However, like any other optimisation problem where it is necessary to find a trade-off among opposite alternatives, e.g., a limited number of resources and a wide set of possible regeneration plans, computational methods by means of computer simulation can be useful.

In this paper, the authors address how computational methods have been applied to modelling CNH in rural areas. To do so, a structured literature review has first been carried out to get the state of the art, and then an analysis and clustering of the results obtained in order to draw some conclusions.

The methods applied in this study to conduct a structured literature review, collect experiences and synthesise knowledge were a combination of the Narrative Literature Review (NLR) and the Systematic Literature Review (SLR). The NLR looks at various studies of a topic and allows the reviewer to obtain an understanding of different views associated with the said topic, making a holistic interpretation of the studies by using his/her experience as well as existing theories and models [8][9]. Other studies [10] point out that NLR is more informal in comparison to the SLR, and it does not necessarily require more rigorous aspects that characterise systematic literature review to be reported; such aspects as research methodology, search term, the database used, and inclusion/exclusion criteria.

A systematic review synthesises research evidence from previous studies based on a strict protocol, ensuring that the most relevant research bases have been considered, while minimising the risk of bias. Systematic reviews make a valuable source of information [8] and are generally considered more scientifically sound than NLR in terms of transparency because findings can be verified more easily by replicating the research setup [11]. This means that the steps related to the review process, especially the search for relevant literature, adheres to a set of clearly defined selection criteria.

Some criteria were established in order to set the scope of this study. References that satisfied all of the following criteria (adapted from [12]) were selected for the review:

- a) published in peer reviewed scientific journals, other academic literature, influential guidelines, handbooks and guidance material;
- b) available in digital form;
- c) written in, or translated to, English or occasionally other languages when relevance is proved; and
- d) published in the last twelve years: 2008–present

3.1. Narrative literature review

The narrative literature review, as previously stated, does not follow the extent of the structured approach that the systematic literature review adopts. The search usually starts from one or more known sources of knowledge and then, based on the available knowledge and information from the previous search-results, further sources of knowledge are identified and relevant knowledge is obtained.

In this paper, the search started from research and development (R&D) projects with a thematic focus on CNH analysis, by first going through projects that the authors' research institutions have been involved in. Then, CORDIS [13] and Google [14] searches were used to find other R&D projects, the former specifically for European projects and the latter for projects beyond. The initial search resulted in 6 R&D projects (see Table 1). Once information on these projects had been obtained, a search for relevant keywords and main outcomes was performed.

For the purpose of this study, the most relevant results from identified research projects were analysed (see Table 1), although

Table 1
R&D projects focused on analysing CNH and whose keywords and findings could be useful for NLR.

Project	Focus/Keywords	Main Findings
RURITAGE	Rural heritage; CNH; sustainable growth; rural landscape mapping tool (Atlas); replication toolbox; monitoring; decision support system (DSS)	New heritage-led rural regeneration paradigm to turn rural areas in sustainable development demonstration laboratories, through their unique CNH potential. Ruritage has identified 6 Systemic Innovation Areas (pilgrimages; sustainable local food production; migration; art and festivals; resilience; and integrated landscape management) which, integrated with cross-cutting themes, showcase heritage potential as an engine for economic, social and environmental development of rural areas [1]
ROCK	Cultural heritage; urban regeneration; sustainable development; economic growth; adaptive reuse	Sharing & Modelling strategy is aimed at creating links between Role Models and Replicator cities using lessons learnt and mentoring process as tools to achieve a systematic set of strategies organised in a model to be implemented in the Replicator Cities. Project is still under development and does not specify if any kind of computational model will be used [63]
CLIC	Circular economy; cultural heritage adaptive reuse; sustainable urban/territorial development; systemic approach; inclusive planning and decision-making	Innovative adaptive re-use models that are culturally, socially and economically inclusive, but it is an ongoing project and lacks of details on how to face that [64]
OpenHeritage	Adaptive re-use of cultural heritage assets; supporting toolbox; database of macro- and micro-level research results	The planning process goes beyond a building or a site to contribute to the transformation of wider areas [65]
STORM	Crowd-sensing; co-creation; data-analytics tools; decision making tools to face climate change and natural hazards	Data analytics service, crowdsourcing services, natural disaster applications, web-based GIS visualisation, threat analysis services, risk assessment tools, mitigation strategy plan. It is mainly focused on conservation of historic structures [66]
HERCULES	Innovative technologies and tools for assessing and mapping cultural landscapes; landscape modelling; community-based Knowledge Hub for Good Landscape Practice	ABM, an especially useful tool to communicate outcomes. It provides a platform for discussion among a diverse group of stakeholders, leading to an integrative negotiation process where definitions and solutions for shared problems could be formulated [51]

some were ongoing at the date of the study. Among them, the RURITAGE, STORM and HERCULES projects are especially relevant. The first deals with the regeneration of rural areas based on their own CNH and through a series of such tools as an Atlas, a DSS (decision support system) or a Monitoring Platform. The next one focuses on decision-making tools to face climate change and natural hazards in cultural heritage sites; while the last one illustrates the use of parameterised Agent-Based Modelling (ABM) for the dynamics simulation of several use-cases. Based on the authors' previous experience and know-how, these additional sources of information have been considered for NLR:

- System Dynamics (SD) application projects: e.g., investment in heritage in Verona (Italy) [15]. SD is suitable for dealing with the nonlinear behaviour of complex systems over time using stocks, flows, internal feedback loops and time delays.
- ABM and Virtual Reality (VR). Research carried out by the Social, Economic and Geographical Sciences Group at the James Hutton Institute, in the Social and Economic dimensions of rural development working area [16]. This research is about ABM and Virtual Reality applied to landscape modelling [17] (the cultural part of the landscape).
- The Socio-Economic Performance Index (SEP index): This index, or numerical score, is intended to measure government policy success in terms of progress towards the Scottish Government's strategic objectives, at the scale of small areas (data zones of 500–1,000 people) in rural areas and small towns in Scotland [18].

3.2. Systematic literature review

The Systematic Literature Review was built on the findings of the NLR and first consisted of the review of a few sample articles published in relevant scientific journals to identify some more keywords and search terms relevant for the purpose of the literature review. As a result, such terms as rural regeneration, rural model, system dynamics (SD), agent-based modelling, virtual/augmented/mixed reality (VR/AR/MR), machine learning (ML) and computational intelligence, among others, were identified.

A representative set of scientific journals were selected to look for relevant papers published within the time frame defined in the literature review criteria. Based on the theme and focus-area of the

journals, the search terms were combined differently in order to ensure as many relevant references as possible could be obtained. Table 2 presents the names of the journals, the impact factor (I. F.) and quartile (Q)¹, the applied search expressions and the number of results obtained.

Just for comparative reasons, a similar search query was performed, but regarding urban areas and smart cities concepts, in order to gain insights about the methods and research that have been carried out at urban level and could be transposed to rural areas. The results show that more than 5 times the number of references were obtained regarding urban areas and smart cities (see Fig. 2 and Tables A.1 and A.2). The results obtained can be refined by adding some filters; in this case, the selected categories are those that are mainly related to computational methods (see Tables A.3 and A.4). After applying the selected refining criteria, the results show that the number of references in urban areas and smart cities is still much higher (273 results) than in the case of rural areas (26 results). Most of the results are related to such issues as logistics, mobility, traffic regulation, waste management, urban growth, etc., so no direct translation from urban to rural use cases in terms of heritage is expected.

3.3. Classification procedure

While analysing the literature found about computational methods applied to modelling rural heritage, some evidence arose e.g., the bibliography on agent-based modelling (ABM) is mostly related to natural heritage issues. In order to establish any possible correlation among the computational methods and the type of cases where they were applied, a reference by reference classification was performed.

Due to the focus of this study on cultural and natural heritage in rural areas, the first decision was to determine the scope of the analysed references, differentiating between rural and urban use-cases. The second classification criterion was the area of application, determining whether the proposed method was addressed to cultural or natural heritage. Due to the difficulty of performing this qualitative classification, while trying to minimise the bias effect, the classification was performed by reaching an agreement among

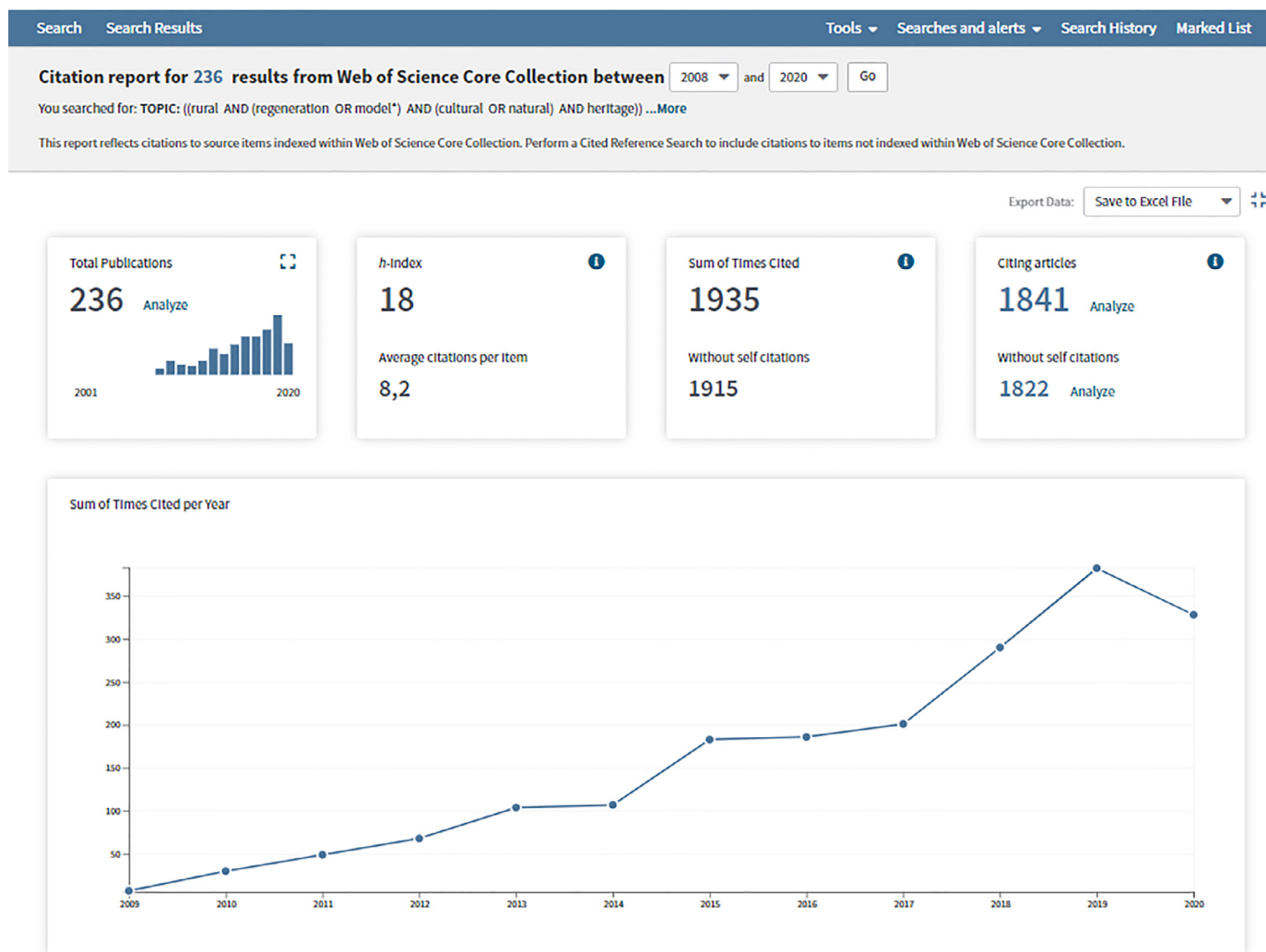
¹ Except for LNAI that is a subseries of Lecture Notes in Computer Science.

Table 2

Number of references obtained through tailored search queries at specific journals

Journal	I. F. (Q)	Search Expression	No.
EXPERT SYSTEMS WITH APPLICATIONS	5.45 (Q1)	((cultural OR natural) AND heritage)	6
JOURNAL OF CULTURAL HERITAGE	2.55 (Q2)	((rural OR regeneration) AND (comput* OR model*))	5
LECTURE NOTES IN COMPUTER SCIENCE	1.17 (Q2)	(comput* AND model* AND (cultural OR natural) AND heritage)	23
LECTURE NOTES IN ARTIFICIAL INTELLIGENCE	-	(comput* AND model* AND (cultural OR natural) AND heritage)	1
		((cultural OR natural) AND heritage)	16
J. ON COMPUTING AND CULTURAL HERITAGE	1.73 (Q3)	(natural heritage)	4
		(cultural heritage)	59

Web of Science

**Fig. 2.** Web of Science citation report. The trend shows an increasing awareness related to computational methods and CNH.

the authors and according to the fuzzy values defined in Fig. 3. Three researchers individually read the papers to determine their relevance and assigned fuzzy values to the scope and application area classification criteria.

When the researchers had made their choices, they compared their findings (fuzzy values). If all had chosen the same fuzzy value for a paper, then it was assigned that value. If an article got different but adjacent fuzzy values e.g., *Strongly Cultural* and *Moderately Cultural*, then that article was assigned the weighted average of the three values. If the assigned fuzzy values were different and not adjacent, then that paper was to be read again by the three researchers in order to evaluate further the relevance of that arti-

cle and agree on the classification; otherwise that article would be omitted from further study. As a result of this round, 34 articles were identified for further study.

The last step was to go through the 34 articles, reading them fully to determine a preliminary identification of the main topic(s). Once the preliminary identification of the topics had been completed, then a process of grouping the topics was begun. This grouping was done based on the understanding that emerged from reading the articles fully and finding the underlying theme of each article. As a result, five major categories or classes were identified: Decision Support Systems (DSS), enhanced heritage, Linked

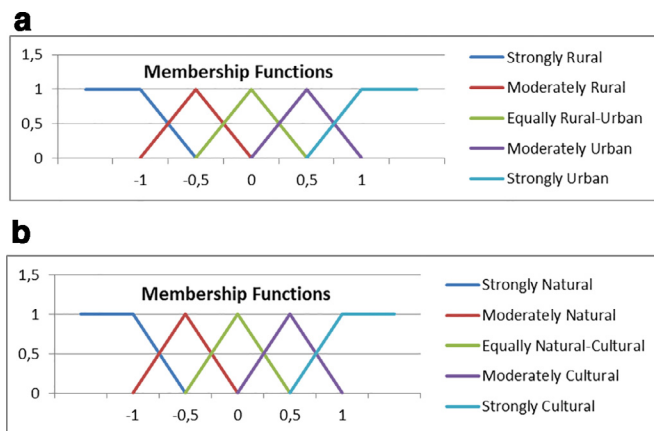


Fig. 3. Fuzzy membership functions defined for easing the qualitative classification step.

Data (LD) and Linked Open Data (LOD), Machine Learning (ML) and Agent-Based Modelling (ABM).

Decision support systems group those computational methods that support enhanced decision-making. Enhanced heritage focuses on computational models related to enhancing the representation or visualisation of cultural heritage assets.

The terms ‘semantic web’ and ‘linked data’ [19] were introduced for the first time in 2006 by Tim Berners-Lee, director of the World Wide Web Consortium (W3C). Linked open data is the combination of open data and linked data.

Machine learning deals with cases where it is hard to tell a machine exactly how to work without specific programming. ML provides the instruction indirectly, conveying the necessary skills by way of examples from which the computer will learn.

An agent-based model is a computer simulation of several decision-makers (agents) that interact through prescribed rules [20]. ABM is a bottom-up tool that has been used to understand complexity in many theoretical and empirical studies. Agents are embedded in and interact with a dynamic environment, learning and adapting according to changes in other agents and the environment.

Table A.5 summarises this classification according to CM, class and the values, for the area of application and the scope assigned by the authors, which have been used for further analysis in following sections.

4. Results

The methods found in the literature were grouped into different clusters or classes, based on their similarities, as explained in the following subsections, e.g., *enhanced heritage* for those methods related to actions based on heritage representation, such as 3D modelling, virtual or augmented reality, serious games and so on; while *DSS* group different kinds of recommender systems.

While analysing the different works, the authors have attempted to go beyond what is stated in the texts, trying to figure out if the methods could also be applied to other cases. For instance, [21] describes a system mainly intended to be used by tourists of cities with cultural heritage related landmarks, but it can also be applied in rural cultural heritage assets. The results of this process are shown in Fig. 4 and Table A.6. According to the analysis performed in our study, not every computational method can be applied to any scope, so the characteristics of the computational methods make them suitable or not, depending on the application area and scope.

The colours in Fig. 4 correspond to the identified clusters and the bubble size depends on the number of references found for each specific case. Points have been represented using jitter, which adds a small amount of random variation to the location of each point as a way of handling overplotting.

4.1. Decision Support Systems

This class groups those computational methods related to technical issues in the support of enhanced decision-making. Tourist assistants and recommendation systems predominate, but also an interesting multi-objective decision-making system for the reuse of historic buildings. As a prototypical example, [22] analyses a recommender system for tourists, suggesting itineraries of cultural events occurring in a region.

There are other examples of methods for calculating users’ similarities and rating predictions on items to be recommended that can be extrapolated to the CNH field, e.g., [23] with a multi-criteria approach that uses Pearson’s correlation coefficient to compute similarities among users. A completely different approach is described in [24], where the authors use Collaborative Reputation Systems (CRS) for the evaluation and classification of the visitors’ behaviour during a cultural event. To achieve data groups that can reflect user classification and allow an understanding of the dynamics related to people’s visiting styles, the K-means partitioning clustering algorithm was used, setting the number of clusters at $K = 4$ (i.e., *A=ant* if it tends to follow a specific path, *B=butterfly* if it is guided by the physical orientation of the exhibits without following a specific path, *F=fish* if it moves around in the centre of the room and *G=grasshopper* if it stops at some preselected artworks). These cases fit within the ‘Consumption/Participation’ stage in the Cultural Cycle (see Fig. 1).

Previous references were centred on people, tourists or visitors; while other references are more focused on CNH assets, as in [25], about decision support for investment in historic buildings. Natural heritage, in the form of historical landscape, has been modelled by means of spatial analysis, involving the digital terrain model in [26]. Regarding the risks that threaten cultural and natural heritage, a Landscape Risk Assessment model (LRA) and Landscape Decision Support System (LDSS) were developed and analysed in [27]. In [28] the author argues for the necessity to develop an inventory or “living map” of the most significant articulations of cultural heritage so as to facilitate active protection and promotion, which is fine, although some other arguments given by the author, e.g., returning to some traditional practices, could be controversial because the quality of life of the rural population should also be considered.

A different approach, which has proved useful to support farmers and designers with enhancing the landscape, is the definition of synthetic parameters capable of expressing the essential architectural features for the analysis of the architectural characteristics of both historical and contemporary rural buildings [29]. A quantification and visualisation of heritage conservation in a neighbourhood is carried out in [30], where the information collected is quantified by the Adapted PageRank Algorithm (APA) and the APA Modified (APAM) to obtain an indicator of heritage conservation.

Decision support systems could be applied in different ways, as in [31], where a two-layer DSS for rural sustainable development (DRSD) is described. It is used to plan socioeconomic development and eco-environmental protection at a county scale. The DRSD considers multiple sectors within a general decision-support framework to generate cross-sector optimal development schemes and includes interesting and detailed *manager-level* and *farmer-level* linear programming models.

Intangible heritage, as part of the cultural heritage (according to the UNESCO Cultural Heritage classification [32]), has also been

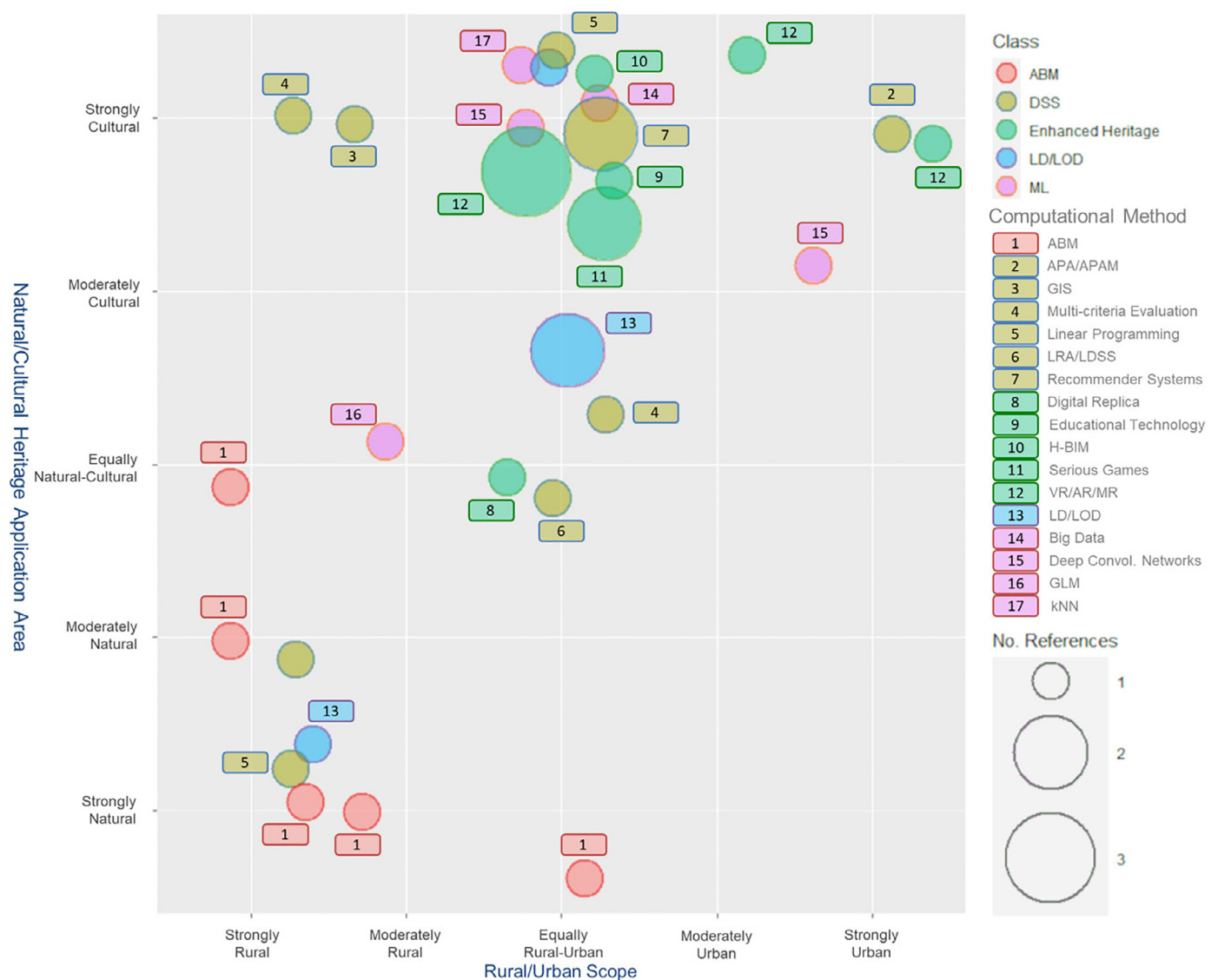


Fig. 4. Distribution of the analysed computational methods, showing some correlations and gaps among the scope, the application area and the class of computational method.

included in the study. In [33] a multi-criteria evaluation for the qualitative verification of the valorisation 'Plans for the Mediterranean Diet' has been developed by several rural municipalities. Effective and strategic tools guide operational decisions in the cultural heritage sector, integrating the different levels of development and connecting the Mediterranean Diet with the landscape and the historical-cultural context. In this case, the 'Production' and 'Dissemination' stages of the Cultural Cycle are involved.

4.2. Enhanced Heritage

Many of the results, when searching for computational models and heritage, are related to enhancing the representation or visualisation of cultural heritage assets. Any mention of the term 'rural' in the search expression turns in zero results, so a simpler expression was used. In this section, 3D modelling of heritage buildings or artefacts [34], digital replicas [35] and virtual/augmented/mixed reality (VR/AR/MR) predominate. Particularly interesting is the extensive and exhaustive survey of AR/VR/MR applied to cultural heritage in [36], where the authors analyse every technology, and every option within those technologies, with application examples.

A different taxonomy of visualisation strategies, more focused on the comprehensive conceptual framework for the classification of possible design choices targeting the visualisation of cultural heritage items, is discussed in [37]. For a more practical application, [38] describes a technique for the model-driven generation of mixed reality virtual environments, where the main contribution is that every modification in contents, visit path and interactions with the physical surrounding environment, do not require a great re-coding effort.

The 3D modelling issues are mainly related to the huge amount of data and the corresponding requested processing power requirements, as well as the efficiency in features extraction and abstraction making. A slightly different approach to 3D modelling issues is that of [39] and [40]. In the first case, a trustworthy solution for surveying cultural sites through laser scanners is shown. The main outcome of this surveying method is that it provides greater accuracy while reducing the processing time. In the second case, BIM tools (Building Information Modelling) combined with GIS tools (Geographical Information System) are presented as effective solutions. These tools make it easier to manage and model graphical data (point clouds) and semantic data (historical-constructive in-

formation), paving the way for future shape recognition algorithms. This is especially relevant for H-BIM (heritage-BIM), i.e., BIM for architectural heritage, allowing the parametric reconstruction of entire buildings directly from point clouds.

Another typical use of 3D modelling of cultural artifacts is in 'serious games' applications. For a complete state-of-the-art analysis of serious games in the humanities and heritage field, see [41]. Concerning the learning process, the authors reference three main types of goals: cognitive, psychomotor and affective, that is, after a learning episode, the learner should have acquired new knowledge, skills, and/or attitudes. Serious games for cultural heritage are particularly suited to the affective domain. An authoring framework supporting all aspects from content design to the final implementation of serious games for cultural heritage, such as the one described in [42], is suitable. However, when dealing not only with development but also with validation, the framework shown in [43] should be taken into account. In a more general sense, [44] discusses the pedagogical impact of technological tools and new educational models and approaches in the field of cultural heritage education.

As previously mentioned, some references are centred on urban examples, as is the case of [45] on the reactivation of cultural heritage, although it is still valid beyond the urban use case and could also be extended to rural areas. The framework presented categorises the type of cultural heritage application to develop, determining which types and quality of resources should be used to provide good usability, while also fitting project requirements.

4.3. Linked Data and Linked Open Data

The semantic web is closely related to ontologies and linked data (LD). An ontology allows a knowledge domain to be formally described in an understandable and usable way for both humans and machines.

Although a limited number of references have been found, the authors decided to keep them due to the envisaged impact that standard vocabularies, such as The Getty Vocabularies [46] and standard ontologies such as the CIDOC CRM [47], would have in CNH and computational methods. One of the examples is [48], where the location-aware semantic search of LOD sources is combined with several general sources from the cultural heritage domain. Linked Open Data sources in isolation are currently too limited to provide interesting semantic information but, combined with each other and with a few other sources, a really informative location-based service can be created.

Another relevant example is [49], where OWL (web ontology language) is used to develop an ontology while arguing over computational methods and tools for the distributed and cooperative annotation of digital resources. Thanks to the annotations, this type of knowledge can produce new types of cultural objects.

In [50], the authors point out some questions and research lines regarding opportunity identification, content selection and contextual delivery, within the framework of personalised cultural heritage experiences for tourists. This links with such standards and methodologies as UserML (User modelling Markup Language) and TourML (Tour Markup Language), which are intended to be standard languages to connect digital assets to cultural heritage items.

The HERCULES project [51] defined a set of 10 operational principles that may guide the design of landscape research. Instead of engaging in fruitless discussions of which model or theory is preferable, the premises that the authors offer can be seen as meta-theoretical guidelines for research projects that tackle long-term changes in the cultural landscapes [52]. For a comparative study of the main ontologies of cultural heritage, see [53].

4.4. Machine Learning

Machines can process huge amounts of data way faster than humans do and they also learn to constantly improve. Endowing computers with learning skills, i.e., algorithms, has opened up new horizons [54]. Of the ML algorithms, some are designed to perform classification tasks. In the field of heritage, these algorithms have been applied to classify heritage assets based on images. For instance, in [21] the authors use the k-nearest neighbour (kNN) for monument recognition by image classification. This image recognition approach is mainly intended to be used by visitors (tourists) to locations with cultural heritage related landmarks (i.e., using a smartphone) to recognise and get information on monuments that they see.

A slightly different approach is described in [55], where social media photos are used to estimate the correlation between landscape attributes and landscape preferences. Social media data are incorporated as evidence of which elements of the landscape are valued, where people are interacting with the landscape, and how these interactions characterise a landscape. However, in [56], the goal is the classification of architectural heritage images by applying Deep Learning, specifically convolutional neural networks, to obtain an automated description of the image based on its content, e.g., a dome, a tower and so on.

As previously stated, ML is a method for training algorithms to develop new behaviours based on experience, i.e., examples, which in some domains is a drawback due to the absence of such huge databases for training. However, more and more information is becoming available for the development of new computational models with the advent of Big Data. With regard to the Cultural Heritage domain, the concept of 'smart' cultural environment introduced in [57] is a good example, following the Internet of Things (IoT) paradigm, where persons (citizens, tourists, etc.) and objects (items, buildings, rooms, etc.) equipped with devices and sensors, GPS, smartphones, cameras, temperature/humidity, etc., can communicate and operate to create a smart context-aware browsing assistant for cultural environments.

Machine Learning fits well when facing complex problems. For instance, in [58], a computer vision method, based on deep convolutional neural networks, is used for the automatic evaluation of the urban environment quality. This allows such issues as 'where the quality of the physical environment is the most dilapidated in the city, that regeneration should be given first consideration' and 'how is the city's appearance changing' to be accurately answered. A similar workflow, properly adapted, could also be applied to rural CNH.

4.5. Agent-Based Modelling (ABM)

Several major advantages credited to ABM have made it powerful in modelling coupled human and natural systems (CHANS). First, ABM has a unique power to model individual decision-making, while incorporating heterogeneity and interaction/feedback. A range of behaviour theories or models, e.g., economic models and bounded rationality theory, can be used to model human decisions and subsequent actions. Second, ABM can incorporate social/ecological processes, structures, norms, and institutional factors. Agents can be created to carry or implement these features, making it possible to '[put] people into place (local social and spatial context)'. This complements the current GIS functionality, which focuses on representing *form* (i.e., 'how the world looks') rather than *process* (i.e., 'how it works'). This advantage makes it technically smooth for coupling human and natural systems in an ABM. For an in-depth review of agent-based simulations of CHANS dynamics, see [59], where several decision models used are analysed, discussing their strengths and weaknesses.

Agent-based modelling is shown to be intuitively received by stakeholders, who significantly contribute to model structure refinement, as in [60] and [61], where ABMs are iteratively constructed in collaboration with the local farming community and experts in landscape research. The model deliberately presents scenarios whose names are connotative of extreme or even unrealistic conditions. The intuitive nature of the ABM is likely to, at least partly, come from the simplicity maintained in the setup of the decision rules (largely composed of 'if-then' queries rather than mathematical expressions). Some drawbacks for ABM in this case are: a) a model refinement process following a stakeholder workshop led to increased process abstraction in an attempt to avoid over-complication, yet risking oversimplification; b) probabilistic processes are present in major, path-dependent, decision-making functions of agents, resulting in the high coefficients of variations; c) it omitted some processes that are fundamental to an accurate assessment of sectorial trade-offs to increase the presentation of the ABM as an exploration of socio-cultural determinants shaping local landscape change processes; d) the model only partially incorporates system ruptures and 'secondary feedback loops'.

A good example of the use of an ABM is in [62], where detailed information on methods, process, agent behaviour and constraints is provided. Although the paper focuses only on farms and farmers, it also deals with environmental issues, such as GHG, and could have some applicability in resilience for rural areas. The use of a coupled economic and agent-based approach provides a range of options for future research.

5. Discussion

According to Fig. 4, the highest concentrations of computational methods are around the area delimited by the SC and ERU labels, followed by the Natural-Rural quadrant; while the gap in the Natural-Urban quadrant is worth noting. Some classes are very well delimited, e.g., ABM and Enhanced Heritage, while others spread through different applications and scopes, such as DSS, LD/LOD and ML. ABM seems to be a suitable option when modelling problems related to natural heritage in rural areas, while enhanced heritage and machine learning fit well when dealing with cultural heritage in either rural or urban areas. In the case of Serious Games, which appears gathered around the Cultural application area, it would be feasible to extend their use to other sectors, e.g., transforming a board-based rural CNH serious game [1] to a computer-based version. Decision support systems, due to their diversity, are the most widely used methods, applicable in almost any application area and scope.

Although Fig. 4 shows some degree of correlation among the class of computational method and its scope and area of application, the authors see the gaps in that figure as opportunities to go further into researching how to apply CM in those areas. This opens up several new scenarios, for instance, a new trend related to nature and urban areas (Natural-Urban quadrant) are the Nature-Based Solutions (NBS) intended for re-naturing cities, and such computational methods as VR/AR, machine learning or DSS can help to foresee the effects of these solutions prior to their development. Moreover, due to its capability to be intuitively received, ABM would make the engagement of stakeholders easier.

As previously stated, most of the references in this study fall into the 'Dissemination', 'Exhibition/ Reception/ Transmission' and 'Consumption/Participation' stages in the Cultural Cycle (see Fig. 1), except for the intangible heritage case in [33] that also involves 'Production' because it describes the process of building a new model to promote the Mediterranean Diet.

6. Conclusions

Computational models are widely studied by researchers and practitioners as suitable methods to study complex systems, in which intuitive analytical solutions are not available. In this paper, a systematic literature review of the state-of-the-art literature on computational methods has been conducted, along with their applications to CNH from 2008 to 2020, to present the available body of knowledge and to analyse the trends in considering computer simulation to numerically study the behaviour of complex systems related to CNH.

This paper shows the correlation between the class of computational method and its scope and area of application, but also proposes some alternative uses in fields where there is less evidence of their applicability. Overall, interest in CNH and rural areas is growing and significant room still exists for development, given the limited number of papers relatively closely related. We believe that this number will continue to increase given the trend shown in this paper.

To the authors' best knowledge, this is the first comprehensive study reviewing the literature that involves computational methods applied to solving real-world cultural and natural heritage problems in rural areas. Although some references were focused on urban or city centres, they have been considered whenever there is a possibility to extend the studies to other areas, e.g., small villages and towns that are often affected by drastic processes of social and economic abandonment.

Declaration of Competing Interest

No.

Acknowledgements

This work has been partially supported by the Regional Government of Castilla y León (Spain), through the Instituto para la Competitividad Empresarial (ICE) and by the European Union HORIZON 2020 research and innovation programme under grant agreement No.: 776465 (RURITAGE).

Supplementary material

Supplementary material associated with this article can be found, in the online version, at [10.1016/j.culher.2021.03.009](https://doi.org/10.1016/j.culher.2021.03.009)

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